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Potential Technology Transfer to the DoD Unmanned Ground Vehicle Program

D. H. Squire

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PREFACE

This IDA study was performed for the Office of the Under Secretary of Defense (Acquisition and Technology) (Strategic and Tactical Systems) under a multitask project[1] that supports the Office of the Secretary of Defense Joint Robotics Program. The study was performed during a summer internship under the direction of Dr. Richard E. Schwartz. He and Dr. David L. Randall, Director of the System Evaluation Division, reviewed the paper. Their helpful comments are gratefully acknowledged.

1 Robotics Review and Assessment, Contract DASW01-94-C-0054, Task Order T-F1-672, 1 March 1990.

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I. INTRODUCTION

A. BACKGROUND

The Joint Robotics Program (JRP), managed by the Office of the Secretary of Defense, is developing unmanned ground vehicles (UGVs) for a number of military applications. These applications currently include scout vehicles, engineer vehicles for mine detection and clearing, security robots, explosive ordnance disposal, and construction-type robots for detecting and removing unexploded ordnance. Future applications may include convoys and other logistic applications, both nonlethal and lethal weapons platforms, and a variety of other applications, such as firefighting, painting, and munitions handlers.

A significant amount of development in the civil sector may be applicable or adaptable to military UGVs.

The purpose of this paper is to identify and describe some of the robotics-related research being conducted outside of the JRP that may be relevant to future programs. This paper focuses on two areas of current research. One is the Automated Highway System (AHS) under development by the Federal Highway Administration (FHWA) (see Chapter II). The second is microrobotics being pursued by numerous organizations for diverse purposes (see Chapter III). In addition to these two areas, a variety of activities of narrower scope are of interest. A few are described briefly in Chapter IV. The information contained in these chapters is largely descriptive. Although suggestions on the potential relevance of these activities are made, those directly involved in JRP developments are in a better position to evaluate the potential of technology transfer from other programs.

B. SUMMARY

The AHS is being developed by a consortium of organizations from Government (the California and U.S. Departments of Transportation), industry (General Motors, Hughes Aircraft, Lockheed-Martin, among others), and academia (Carnegie Mellon,

University of California-Berkeley). It is in the early stages; a technology development plan is nearing completion. The goal is fully autonomous vehicle travel, hands off, feet off, and brain off. Large investments are planned to make the AHS a reality. It seems very likely that much of the technology that will have to be developed for AHS (other than technology that relies on features embedded in the highway) will prove applicable to military UGVs. In addition to the AHS program, the automobile industry is active in developing advanced sensors for installation on cars, including accelerometers for air-bag deployment, pressure sensors for monitoring tires, and onboard diagnostic systems.

Future UGV projects stand to gain much from the development of microrobotics and microelectromechanical system (MEMS) technology. Well-developed microsensors could be invaluable for enhancing mobility/perception and reconnaissance, surveillance, and target acquisition (RSTA) functions on UGVs, as well as for reducing the cost of many of these systems. Achievements on inertial guidance systems through the incorporation of MEMS accelerometers and gyroscopes could also contribute to improved navigation and driving of unmanned platforms.

In addition to these system enhancements, new military applications are possible with microrobotics. A sensor net concept is suggested as one such possibility in which UGVs might play a role. The resources already employed throughout industry and Government in the development of microrobotics and MEMS are large. The Defense Advanced Researach Projects Agency (DARPA) cited U.S. expenditures in 1995 on MEMS technology alone in the vicinity of $130 million [Ref. 4].

Since its inception, the JRP has leveraged previous and ongoing technology developments. Such leveraging may be even more important in the future as the field of robotics grows and the military application of UGVs expands. The AHS program and the general areas of microrobotics and MEMS are promising candidates for future technology for JRP projects.

II. THE AUTOMATED HIGHWAY SYSTEM

The Automated Highway System (AHS) Program was initiated by the Federal Highway Administration (FHWA) in 1992 as part of the Department of Transportation's efforts to develop a transportation system for the future. The first stage of this program included the formation of the National Automated Highway System Consortium (NAHSC) and was a joint effort by research teams from Government, industry, and academia. These teams aimed at analyzing the available technology base, projecting the capabilities that must be developed for incorporation into the AHS, and examining how best to pursue those technological advancements.

The results of these studies were compiled in a report produced by the MITRE Corporation, dated 27 April 1995, titled *Summary and Assessment of Findings from the Precursor Analyses of Automated Highway Systems.* The required capabilities of the AHS, as laid out in this report, fall under two main categories: system-related and vehicle-related. Within the former category, researchers are primarily concerned with system safety. There are two reasons for this. First, because the AHS will be marketed to the user, the general public will have to trust it and be willing to use it. Second, increased safety is considered a chief benefit of the AHS, and without this feature the project would lose much of its allure. Developers working on unmanned ground vehicles (UGVs) must address many of the same issues involved in making the AHS safe.

Within the second category, vehicle-related capabilities, two concerns mentioned in the report stand out as being particularly relevant to the UGV effort: sensor technologies and advanced vehicle controls.

A. SPECIFIC TECHNOLOGIES

1. Vehicle Controls

Although vehicle sensors and vehicle controls must work together for both navigation and driving, it is possible to discuss them separately. Here, attention will be given first to existing and projected control capabilities and next to advances in sensor

technologies. Navigation spans the two areas but in this discussion is incorporated in the controls section. Vehicle control is divided into three subsections: vehicle stabilization capabilities, lateral/longitudinal controls, and navigation.

Vehicle stabilization is the most mundane of the three aspects of vehicle controls and is, by far, the most advanced to date. Robotics technology developed for the automobile began with the desire to increase the safety of vehicles without drastically altering their operation (as integration of AHS capabilities will certainly do). Thus, early vehicle automation consisted of improving existing systems through greater reliance on computers in a manner that would not require the driver's attention. The first step in this direction was the introduction of anti-lock braking systems (ABS), a feature that has already become standard on many automobiles. With ABS, the system monitors wheel rotation during braking and automatically releases and reapplies the brakes rapidly in order to prevent skidding. Along the same lines, traction control systems were developed to perform the same function of preventing tire slippage during acceleration. Several other technologically advanced systems for vehicle stabilization are in various stages of development. Four-wheel steering systems provide separate control of the front and rear wheels to improve safety and performance in different maneuvering situations. Active suspension systems allow for a smoother ride without sacrificing handling ability by automatically varying spring and damper rates to suit the driving condition. Finally, ABS and traction control systems are being further enhanced to measure speed, angle, lateral acceleration, and vehicle rotation around its vertical axis to provide separate braking pressure to specific wheels in order to prevent spin-outs [Ref. 22]. All of these stabilization features are designed with safety of manned vehicles in mind. They may also be applied to UGVs, and they represent the beginnings of the AHS concept.

The second area of control capabilities, the actual automation of driving, can be broken down into lateral and longitudinal controls. Lateral control includes lane positioning, detecting vehicles in other lanes, maneuvering to change lanes, and entering and exiting the AHS system. Longitudinal control comprises two main functions: (1) maintaining a safe spacing to the front and rear of the vehicle and (2) detecting obstacles in the longitudinal plane. To date, lateral and longitudinal control have largely been developed separately.

Lane positioning has been approached with several different sensing methods. The simplest, and a favorite among researchers, is the use of magnetic nails in the roadway.

This technique requires no additional power, functions in all weather conditions, and allows for graceful degradation since the failure of one or two nails does not disrupt the system. Other experimental lateral control techniques include a magnetic stripe in the roadway, a field generated by an "active" wire in or above the road, vision-based sensing, and fixed-position infrastructure beacons [Ref. 11]. Of these, only vision-based sensing has shown additional promise and is discussed below.

Another aspect of lateral control, steering, has also received due attention. The conventional wisdom surrounding reliable automated steering proposes a shift from current mechanically linked systems to electrically actuated techniques in which a computer translates control directions (steering, throttle, brake) into a voltage, which, in turn, actuates the control movement. The NAHSC has made this "drive-by-wire" technology one of its foci, citing greater simplicity, improved performance, and overall system flexibility as advantages [Ref. 22].

Carnegie Mellon University (CMU), through its Robotics Institute, has also made significant contributions to the evolution of automated steering. Its NavLab project has focused on producing an autonomous steering capability that does not rely on the existence of an infrastructure like the AHS, thus making it much more applicable to military unmanned vehicles. Carnegie Mellon recently demonstrated its technology achievements with the No Hands Across America trip in which two CMU researchers drove the NavLab 5 platform from Pittsburgh, PA, to San Diego, CA, with the RALPH computer program performing 98.2 percent of the driving (while the human passengers controlled the throttle and brake) [Ref. 15].

The first step in the Carnegie Mellon project was the development of the Autonomous Land Vehicle in a Neural Network (ALVINN), a perception system that learns to drive by watching a person drive. This learning process takes as long as 3 minutes, in which time the ALVINN system adapts its driving knowledge base to the specific road type and conditions present. Using this technology, ALVINN networks have been able to learn to navigate single-lane dirt roads, single-lane paved bike paths, two-lane suburban streets, and lined divided highways [Ref. 14]. ALVINN suffers from several limitations, however, including the required training period necessary whenever the road type or conditions change and the need for human intervention in that training process. The Rapidly Adapting Lateral Position Handler (RALPH) system architecture was therefore developed. RALPH corrects ALVINN's problems by breaking down the

steering process into three separate activities: sampling the image, determining the road curvature, and measuring the lateral offset of the vehicle relative to the lane center. The separation of the image-sampling function allows RALPH to adapt quickly to changes in the road by remembering previous experiences and by reverting to the appropriate driving technique in each situation [Ref. 16]. A necessary future step for the Carnegie Mellon NavLab project is to incorporate obstacle detection and avoidance capabilities.

Implementing longitudinal control methods has been a less difficult task than achieving lateral positioning and steering. Here, the primary concern is integrating sensors and actuators to monitor the spacing between vehicles and to maintain a safe distance. Such systems, called autonomous intelligent cruise control (AICC), have actually reached the prototype phase. Some are designed to simply monitor spacing and alert the driver when the separation distance becomes too narrow or the closing speed too high. Others are capable of adjusting the vehicle's speed to maintain a set distance [Ref. 22]. The most popular technique for achieving longitudinal control has been the use of radar. Installed at both the front and rear of the vehicle, sensors would scan at azimuth angles of $\pm 45^{\circ}$, thus providing some limited integration between longitudinal and lateral control in order to determine spaces for lane changing and merging [Ref. 11].

As control strategies have advanced, this integration of lateral and longitudinal control has become more of a concern. The University of California at Berkeley, a leader in intelligent transportation research with its PATH (Partners for Advanced Transit and Highways) Project, has made development towards that end one of its chief areas of focus. This research involves the use of machine vision-based guidance to augment the separate lateral and longitudinal control methods and to provide greater total control. Line flow technology would be incorporated to provide greater lateral information about road curvature. For additional longitudinal information, useful in detecting unexpected obstacles that could be missed by radar, binocular stereopsis technology would be used. As mentioned, control integration is particularly useful in executing a lane change or during entry and exit from the system. Here, stereopsis would provide a better all-around picture of the immediate driving environment than radar sensors, and line flow would act as an additional control variable during the maneuver itself [Ref. 38].

The final area of vehicle control is navigation. Although magnetic, vision, and range sensors can be employed to monitor the vehicle's immediate surroundings and permit automated control, the vehicle must also have some knowledge of where it is in the

world in order to allow for complete autonomous driving. Currently, navigation technology in automobiles is limited in its commercial applications to computer mapping systems, which provide drivers with autonomous route planning capabilities; Sony, Delco Electronics, and Oldsmobile have all marketed such devices [Ref. 7]. This technology needs to be further matured, however, in order to integrate it with other autonomous control capabilities for complete unmanned maneuverability.

The development of advanced navigation systems is another area on which Berkeley researchers involved with the PATH project have focused. As with their vehicle control strategy, their approach here has been to integrate existing technologies—GPS-based and inertial measurement—to provide a more complete and efficient system. Carrier-phase GPS navigation, which can provide very accurate positioning, has been the favorite technique, but it suffers several limitations. It does not function well under a canopy (which includes trees, tall buildings, tunnels, and so forth) because the vehicle must maintain contact with at least three satellites to determine its global position. In addition, atmospheric delays caused by weather, clock differences, and receiver noise can all create sufficient error to degrade system performance. An alternative method for navigation is inertial guidance. The primary problem with applicable inertial sensors is that they are only able to maintain a precise course for a few minutes before drift occurs. The integration of these two systems, however, with GPS providing a periodic "fix" while the rest of the navigating is done by inertial measurement, offers an effective solution [Ref. 38]. The development of micro sensors such as MEMS gyroscopes (discussed in Chapter III) makes the realization of integrated navigation systems even more practical.

2. Sensors

In addition to playing an integral role in vehicle control and navigation, advanced sensors are essential for obstacle detection. Their development is important for the realization of robust in-vehicle collision warning and avoidance systems. Thus far, technology is limited to obstacle detection; autonomous collision avoidance systems is forecast as the next step in the AHS development. Several near-obstacle detection systems (NODS) have been developed; a few have even reached the production stage. One type of NODS is a rear-looking sensor that operates only when the vehicle is put in reverse and warns the driver of small obstacles, such as pets or children, behind the vehicle. Another type of NODS has been produced by Delco Electronics, one of the

members of the NAHSC. Its Forewarn system, for installation on school buses, alerts the driver to obstacles in his blindspots [Ref. 22]. Cadillac has also brought the Forewarn system to market on several models. It works as follows: as the gap between cars closes, a yellow road-hazard symbol is reflected off the inside of the windshield by a heads-up display mounted on the dashboard, and a series of chimes sound. As the gap narrows further, a red stop sign flashes off the windshield, the car shouts "Brake! Brake! Brake!" and the brakes are momentarily spiked to jolt the driver to action [Ref. 45].

The NAHSC has chosen the development of sensor technologies as one of its chief projects, the general consensus being that smaller, better, cheaper sensors will make the AHS, as a whole, a more realistic vision. The sensors themselves are already fairly well-developed, with the primary concern now being miniaturization (which is discussed in greater detail in the next chapter) [Ref. 22]. The technology necessary to convert obstacle warning systems into obstacle avoidance systems, however, is still under development. This is also a focus of Berkeley's PATH project, which has also devoted significant attention to developing better bridges between sensors and actuators. The current state of technology does not allow individual sensors to provide precise information concerning obstacle detection and positioning and also to operate at high update rates, both of which are necessary for fully autonomous control. The Berkeley Sensor and Actuator Center is investigating data fusion to correct this shortcoming. This research comprises two steps. First, efforts are aimed at developing three low-cost, high-performance microsensors: a force-balanced microaccelerometer, a vibrating rate gyroscope, and an ultrasonic microphone and transducer. Second, these sensors must be integrated in such a way that their fused outputs can provide accurate data and information for transfer to actuators in a real-time framework [Ref. 38].

3. Safety Issues

Heightened safety promises to be one of the chief benefits of the development of an Automated Highway System. The two primary technology strategies for ensuring safety in autonomously controlled vehicles are system redundancy to decrease the likelihood of threatening malfunctions and onboard diagnostic systems to monitor the state of the vehicle and the driver. When researchers consider some of these same technologies for military applications such as those being developed by the JRP, the level of safety required or desired becomes a key issue. For the AHS, the safety concerns are simple:

"safety first"; as a consumer product, the system must cater to the individual user—the average driver—and in this respect must be viewed as being at least as safe as the current highway system.

B. POTENTIAL FOR TECHNOLOGY TRANSFER

To the extent that the AHS program relies on components that are external to the transiting vehicles, the applicability of the corresponding technology to military UGVs is unlikely. To the extent that the AHS program relies on self-contained onboard capabilities, it is likely that the corresponding technology would be applicable to certain potential military applications of UGVs. To the extent that onboard capabilities are commercialized, they should be very affordable for military UGVs.

A variety of self-contained, onboard controls and sensors were discussed in the preceding sections. Most of this technology will involve sophisticated software for processing and integration. Depending on the applications that are pursued, almost all of this technology could be applied to military UGVs. (Some of the technology could also be applied to manned vehicles.)

Safety will be the sine qua non of the AHS. Hence, it is likely that onboard robotic safety features will be a major emphasis of the AHS program. Within the JRP, it has not yet been necessary to focus on safety of military UGVs. Some applications of UGVs may not involve difficult safety issues. However, many potential applications will pose significant safety concerns that will have to be resolved before a UGV system is fielded.

The severity and character of the safety issues will depend on the specifics of both the application and the UGV implementation for that application. Application specifics include the following:

- The proximity of non-UGV military or civilian personnel to the UGV
- The proximity of non-UGV vehicular traffic, military or civilian, to the UGV
- The extent to which the UGV operating environment can be controlled
- The extent to which the UGV operator will be aware of the presence of non-UGV elements
- The presence of hazardous materials that could accidentally be released or detonated by the UGV.

Implementation specifics include the following:

- Size and speed of the UGV (kinetic energy)
- Presence and type of manipulators that are capable of causing damage or injury
- Presence and type of weapons on the UGV
- Level of autonomy of the UGV
- Specific design features that affect safety positively or negatively.

The various factors listed above and their effect on safety issues may depend on whether the application occurs in peacetime (e.g., in training) or in wartime. For example, in wartime military control of roads is often permitted. Moreover, if the primary purpose of the UGV is to save lives in wartime and it fulfills that purpose, safety consideration might be relaxed in wartime.

On balance it seems likely that safety issues will be a serious concern for many UGV applications. User trust will be an important ingredient in successful fielding of UGV systems. Also, safety issues are likely to conflict with the fact that for many applications, the greatest payoffs will be realized by highly autonomous UGV systems. Since safety will be emphasized in AHS, military application of the AHS technology and software developed specifically for reasons of safety deserve continued investigation.

III. MICROROBOTICS

Dr. George Bekey, a professor at the University of Southern California and the current president of the IEEE Robotics and Automation Society, declared in his President's Letter, which appeared in the September issue of *IEEE Robotics and Automation*, "My message this month: Think small! I believe that one of the significant trends in our field is toward smaller systems, on many levels." As this statement reflects, the field of microrobotics has grown in recent years and could prove extremely useful in the future development of unmanned systems. As scientists and engineers have sought to drastically reduce the size of sensors, actuators, processors, and other robotics components, they have realized advantages in terms of better performance, lower costs, and new applications. Advances in microrobotics have potential uses in industry, medicine, defense, and space exploration. As a result, numerous organizations are developing microrobotics, including universities, private research institutions, and Government agencies.

Microrobotics represents an extensive field without a clear boundary that defines a "micro" system. Devices, ranging from a meter scale down to a millimeter or even micrometer scale, are all referred to as "microrobotics." In addition, macro-sized platforms with micro manipulation capabilities—the ability to provide fine precision handling at the tips of manipulators—have also been grouped with microrobotics; examples of these include scanning tunneling microscopes and electromagnetic cell sorters used in bioengineering [Ref. 5]. Thus, the microrobotics technologies that have evolved and the applications that have reached fruition can be as different from one another as they are from other robotic systems.

A. MICROELECTROMECHANICAL SYSTEMS (MEMS)

One critical technology used in the production of microrobots is microelectromechanical systems, or MEMS. Having arrived on the scene only in the last decade, these tiny devices are gaining popularity within the robotics research community as a novel approach in making platforms smaller and more capable. Promising to serve as

the building blocks for robotics systems in the next century, MEMS have become an international focus, with Europe, Japan, and the United States all spending large sums of money on their development.

MEMS do not involve a specific fabrication process or material, nor do they represent a complete system in and of themselves. Rather, they are the micro-scaled sensors and actuators that serve as the enabling pieces in a wide variety of larger systems. In general, MEMS have three defining characteristics: (1) they combine microelectronics and electromechanical components to permit sensors, actuators, and intelligence to be merged into one closed-loop system; (2) this is done in an extremely small, light-weight package only a few millimeters in size; and (3) the production is done through batch fabrication, making it as easy and inexpensive to produce one million units as to produce only one [Ref. 19].

Several technologies have evolved for the fabrication of MEMS devices. The earliest technique, bulk-micromachining, was developed in the 1960s. It uses lyes to etch silicon wafers in a desired pattern. This method is useful in producing certain types of sensors. The second method, surface-micromachining, is similar to the first, but combines layers of different silicon compounds in the production process. Here, a sacrificial layer (usually of silicon-dioxide) is added to a several micron-thick structural layer (of polysilicon) and then selectively etched off to produce the micromechanical device. This technique is particularly useful in producing micromotors and other types of actuators. The third and most sophisticated fabrication method is the LIGA-Process, developed at a research center in Karlsruhe, Germany. This process combines x-ray lithography, galvanic casting, and micromolding technology and can be used to produce a variety of sensors and actuators. This method also allows for materials other than silicon to be used, such as plastics and metals, and provides greater flexibility for mass production [Ref. 39].

With the rapid advances in micromechanical technologies, MEMS have emerged as a critical technology in the evolution of all robotics. The Defense Advanced Research Projects Agency (DARPA), under Electronics Technology Office Program Manager Kaigham Gabriel, has taken a leading role in the research and development of MEMS. The DARPA program is divided into four focus areas: fluid sensing and control, inertial measurement, electromagnetic/optical beam steering, and distributed networks. Within those classifications, DARPA is funding a host of projects through university programs (at Case Western, UCLA, Michigan, Cornell, and others), industry (Westinghouse, IBM,

General Electric, Honeywell, and others), and Government laboratories (Livermore and Sandia Laboratories) [Ref. 20]. Gabriel cites the primary benefit expected from continued MEMS development: "Micromechanical devices will supply electronic systems with a much needed window to the physical world, allowing them to sense and control motion, light, sound, heat, and other physical forces" [Ref. 6]. With the emergence of MEMS and other technologies, a major direction in robotics is towards "thinking small." The applications and other advantages that have and will continue to result from this trend are numerous.

B. APPLICATIONS

The applications of microrobotics that have been realized and those that are still being developed is extensive. A breakdown by industry is the best way to exhibit the wide variety of uses and fields to which microrobotics technology can be applied.

1. Industrial Applications

The earliest ventures into microrobotics were commercially driven, and industry still remains the research leader in the field. A host of industrial applications in various areas have been considered and are in various stages of development and production. One leading use for mobile robots in general and for minirobots specifically is to minimize human operations in hazardous environments. This is the justification for the Reduced Access Characterization System (RACS), developed jointly by IS Robotics[1] and the Department of Energy (DOE's) Idaho National Energy Laboratories. With the need to decontaminate, and decommission numerous facilities long exposed to radiation, a method for surveying and characterizing these areas before and during cleanup became necessary. To remove humans from this dangerous task, RACS (better classified as a minirobot than a micro one) has been developed to provide automated radiological data collection and storage. Already in use by DOE, RACS is capable of collision avoidance using infrared (IR) sensors and communication with a homing beacon via radio frequency, and gathers data with a scintillating radiation detector [Refs. 23 and 25].

1 A company founded by members from MIT's Artificial Intelligence Laboratory and NASA's Jet Propulsion Laboratory to develop and market small robots.

Another hazardous environment in which mini- and microrobots are being employed is nuclear power plants. Sandia National Laboratories has developed its SMART software (Sequential Modular Architecture for Robotics and Teleoperation), which is used to control robotic arms for cleanup inside underground storage tanks containing radiological and other types of hazardous materials, as well as other places where humans cannot go [Ref. 24]. Work has also been done to reduce the size of robotic devices to the point that they can fit inside pipes, in nuclear plants, and elsewhere, in order to perform inspection and maintenance tasks. Researchers have experimented with two propulsion methods for these devices. The first employs a "giant magnetostrictive alloy" actuator to drive via a magnetic field. The second propulsion technique utilizes a more mechanical "inchworm" motion [Ref. 39].

The Micromachine Center in Japan, funded by MITI, has developed a pipe inspection device that moves by this latter technique. Researchers there have produced a micromachine, measuring only 5.5 mm in diameter and 20 mm in length, capable of fitting in and navigating a pipe with a diameter of 8 mm. The device moves at a rate of 6 mm/sec while searching for micron-order cracks. The program envisions an entire microsystem, consisting of this inspection tool and a future module capable of repairing the irregularities detected by its counterpart [Ref. 28]. The Micromachine Center is engaged in other projects as well, including the development of medical applications. In addition to the pipe inspection tool, they have produced other actuators on a millimeter scale such as micro pumps and motors. Several of these devices are pictured in Appendix A along with brief descriptions of their operation.

The automotive industry is another area actively developing microrobotics. MEMS devices already have numerous uses in automobiles, including airbag, anti-lock brake, and air conditioning systems. Other applications involve similar sensors being used to provide continuous monitoring of various systems; these could be deployed in tires to optimize air pressure and in fuel injection to minimize gas consumption [Ref. 39]. Together, these automotive improvements would serve to reduce consumer expenditures on fuel and maintenance and extend car life. Many of these technological advancements being made in the automotive industry could be directly transferred to unmanned vehicles. Without a human operator, the need for automated monitoring vehicle status and function may be greater than in manned vehicles.

2. Medical Applications

Perhaps the broadest civilian use for microrobotics comes in the medical field. The most widely researched medical application area is in the development of microsurgical techniques, ranging from micromanipulation tools for use by surgeons to autonomous microrobots capable of traveling inside the body to perform surgical procedures on their own. NASA's Jet Propulsion Laboratory, in cooperation with MicroDexterity Systems, Inc., has been working on a Robot-Assisted MicroSurgery (RAMS) workstation. This will provide surgeons operating in close quarters, e.g., on the brain, eye, ear, nose, throat, and face, with a small six-degrees-of-freedom teleoperated manipulator. To enable more delicate surgical procedures in these areas, the RAMS slave arm is capable of accurate positioning to 25 microns. It will also eliminate involuntary jerk and tremor movements made by the operating surgeon [Ref. 32].

Further research and development into microsurgical applications could place the surgeon in a supervisory role. For several years, students in the Artificial Intelligence Laboratory at MIT have been working on a microrobotic device capable of navigating, inspecting, and eventually performing surgery on the human colon and lower intestine. Currently, the robot, called Cleo, is powered by 10,000-rpm motors and worm drives and travels on two treads that can grip the interior lining of the intestine without damaging it. The "vehicle" is equipped with sensors to detect visible light, infrared, tilt, and obstacles; a claw to grasp and carry objects; and an onboard battery, all of which is sealed against the hostile environment of the human intestine. However, it still must trail behind it (and out of the patient) an air hose, vacuum hose, video cable, and power line for a camera and floodlight. The device also needs to be reduced in size further because it still measures an inch in diameter [Refs. 8 and 9]. Nevertheless, while actual testing in a human patient remains a goal for the future, the technology to make it all possible is emerging.

Several additional medical applications are also being pursued and are worthy of note. Researchers at the University of California-Berkeley have developed a silicon light bulb that can be fitted to a hypodermic needle along with an optical sensor to perform biopsies on suspicious lumps. Scientists at Carnegie Mellon University have designed a rotor with blades the width of human hairs to be deployed in the blood stream to detect whether circulation is being obstructed by atherosclerosis. Finally, work is being done at the University of Minnesota on a microrobotic device that uses static electricity to open and close valves, causing an attached pump to vibrate and push liquid out behind it. Such

a device could be used to dispense drugs to specific locations in the body, thus reducing drug side effects. It would also make life easier for diabetics who must regularly give themselves insulin shots [Ref. 12].

3. Space Exploration

Space exploration is another area rich with opportunities for microrobotics applications. NASA's Jet Propulsion Laboratory has been the most active research organization in this field, especially through its Center for Space Microelectronics Technology. For NASA, the primary aim of developing microrobotics technology is to lower mission cost by reducing system size and mass. One example of this is the *Kuiper Express* project, which proposed a completely new spacecraft small enough to be powered by a small ion engine fueled by two solar panels [Ref. 3].

4. Military Applications

Microrobotics offers its own advantages to the defense industry. While application possibilities run along the entire spectrum from logistical and C4 capabilities to weapons and battlefield technologies, the primary role for microrobotics applied to military systems is in improving existing systems, making them smaller, cheaper, and more reliable and thus helping to save dollars and lives. The Department of Defense (DoD) recognizes many of these potential military uses of MEMS in its December 1995 report, *Microelectromechanical Systems Opportunities.*

One area in which DoD is particularly active concerns systems which require inertial sensors. By replacing conventional sensors essential to inertial guidance units with MEMS accelerometers and gyroscopes, the cost of these systems can be brought down drastically without sacrificing performance or reliability. This makes them practical for a host of uses [Ref. 2]. (For comparison between conventional and MEMS inertial measurement units, see Appendix A.) Replacing explosive warhead fuzing and safe-arming components with MEMS devices is another application, and Lawrence Livermore National Laboratory, among others, has been working in this respect [Ref. 10]. Along the same lines, researchers have developed (originally for automobile airbag systems) a unique microaccelerometer. It has a self-test capability which could significantly improve bomb reliability [Ref. 4]. MEMS inertial guidance units could also be fitted on conventional

munitions, reducing the reliance on unguided ordnance. Finally, personal, hand-held navigation systems could be developed for use by the individual soldier [Ref. 2].

Another component of military systems that could draw heavily from developments in microrobotics technology is sensors. Researchers have demonstrated great promise in the application of MEMS technology to all manner of sensors: pressure, chemical, thermal, acoustic, magnetic, and radio frequency. One use for such devices in military vehicles, perhaps especially in UGVs, is continually operating maintenance systems, similar to those mentioned previously in connection with the automotive industry. Embedding MEMS sensors in critical vehicle systems would allow for monitoring the health of those systems without wasting time and money on unnecessary inspections [Ref. 2]. Dennis Polla, in his Defense Science Study Group paper "Fatigue Monitoring of Critical Aircraft Components Using Multiple Microsensors," addresses the feasibility of such a system as applied to aircraft and proposes the technology necessary to develop it. Other potential military applications of microsensors are miniature analytical instruments for detecting and identifying substances, such as fuels, chemicals, and drugs. These microsensors could be built small and inexpensively enough to be deployed at the individual soldier level. In addition, advanced identification-friend-or-foe (IFF) devices could provide secure communications in a self-contained, smaller, faster, and more durable package than currently possible [Refs. 1 and 2].

In addition to enhancements of existing systems, microrobotics technology offers new possibilities for the military as well. One potential application of MEMS sensor technology involves the development of distributed sensor nets. Under such a scenario, tiny, disposable devices would be distributed over a designated area, e.g., by aircraft. These sensors would be capable of collecting, processing, and storing data about their immediate surroundings, and possibly even communicating with each other for coordinated sensing efforts. This information could then be retrieved and recorded by a high-flying aircraft equipped with a laser for signaling the microsensors on the ground. The potential uses for such a sensor net are varied and include characterizing terrain to determine vehicle trafficability, relaying communications, and even developing a battlefield sensor net for continuous monitoring of enemy activities over critical areas of the battlefield [Ref. 1].

Another novel application for microtechnology currently under development is active surfaces. These are thin, rapidly changeable surfaces that could either be embedded

or retrofitted on military platforms to serve a number of purposes. One potential use is to improve vehicle camouflage. Small plates could be added to the exterior of military vehicles that are capable of reorienting themselves relative to an observer in order to match the background. One method for doing this might involve using micropumps to move various colored dyes about the surface. Another type of active surface concerns improving the aerodynamics of aircraft. This could be done by employing MEMS sensors and actuators to monitor air pressure, speed, and turbulence along the surface of the plane and then adjusting the air flow through tiny vents, thus making the aircraft more efficient in lift and maneuverability. Additionally, a similar system could be implemented on submarines to reduce noise [Ref. 1].

A final military application of microrobotics, and the one furthest along the technology timeline, introduces the possibility of designing microweapons called Microrobotic Electronic Disabling System (MEDS). MEDS would consist of a fleet of small devices capable of infesting and attacking the electronics components of an enemy's systems. Each individual robot would conceivably consist of five subsystems. First, location sensors would home in on electronics (up to a distance of only about 10 meters, making precise dispersion of the devices in the immediate vicinity of the target necessary). Next, a mobility system, composed of a data processing unit and autonomous navigation and locomotion capabilities, would allow the MEDS to invade the target. Finally, a kill mechanism would dispense a caustic or otherwise destructive fluid to sabotage the electronics components. The remaining two subsystems would be a communications device to permit a coordinated attack and a power source. All of this is to be integrated in a 3 mm^2 package (a drawing of what the proposed MEDS device would look like is provided in Appendix A) [Ref. 1]. Because of the limited mobility of the individual MEDS, their deployment would need to be precision guided. However, their utility as a countervalue weapon could be great. Distributed over an enemy's infrastructure, they could achieve vast destruction of essential industry and C4 systems with little collateral damage [Ref. 1]. In addition, these devices could prove useful in peacekeeping missions, deployed to disable the military equipment of both sides of a regional dispute without risking human lives [Ref. 12].

C. POTENTIAL FOR TECHNOLOGY TRANSFER

In time, microrobotics in general and MEMS in particular are likely to have important UGV applications. To date, the JRP has not been concerned with very small robots, but there is growing interest in this area. Microrobots offer the following potential advantages:

- Missions that require fitting into and traversing very narrow spaces cannot be performed by conventional vehicles or by personnel.
- Small size is conducive to
  - Stealth
  - Low cost
  - Easy transportability (including portability)
  - Expandability
  - Proliferated robots.

MEMS can make microrobots practical through the development of useful mission packages that fit on very small UGVs. In addition, MEMS will have many applications to larger vehicles, both manned and unmanned. By creating new UGV missions, e.g., employing MEMS sensors, increasing the reliability of UGV operation, and lowering the cost of UGVs. MEMS are likely to have a very positive influence on the development of larger UGVs.

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IV. ADDITIONAL AREAS OF ROBOTICS RESEARCH AND DEVELOPMENT

This chapter is a brief discussion of some additional robotics activities. Many of these activities are sponsored by DoD and a few of them have been leveraged in the technology development efforts under the JRP

One growing source for robotics research is the network of national laboratories under the supervision of the Department of Energy. Sandia National Laboratory has been developing robotics technologies and unmanned vehicle capabilities in particular. One of its first endeavors was the design of the Fire Ant platform. Intended for battlefield use, the Fire Ant was a teleoperated anti-tank weapon. It was equipped with a small camera to transmit images back to the soldier responsible for controlling it, and when it spotted a tank, it could autonomously fire a 22-pound anti-armor slug capable of destroying a target at a range of 550 yards. The Fire Ant never went beyond the experimental stage [Ref. 12]. Sandia also created the Robotics Vehicle Range, the focus of which has been toward developing military applications for mobile robots. Using this range, Sandia has developed a number of UGVs including the Surveillance and Reconnaissance Ground Equipment (SARGE) vehicle that is being used in the JRP. Also developed was the HAGAR platform, a smaller, more agile vehicle with centerline articulation suited for military missions requiring stealth [Ref. 37].

Oak Ridge National Laboratory is another Government lab engaged in robotics research. Two of its divisions are developing technologies related to unmanned ground vehicle applications. First, the Oak Ridge Transportation Technology Center (ORTRAN) is responsible for leading DOE's research activities concerning the development of intelligent vehicle highway systems, as described in Chapter II. In this capacity, ORTRAN is participating in cooperative agreements with the U.S. Department of Transportation (DoT) and numerous universities to promote the development of advanced vehicle capabilities [Ref. 34].

The second division involved with robotics at Oak Ridge is the Robotics and Process Systems Division (RPSD). Its Ammunition Logistics Program is concerned with

the evolution of various automated ammunition resupply technologies. The first project conducted under this program resulted in the development of the Future Armor Rearm System (FARS). FARS is composed of a tracked, armored chassis in which the soldier operating the system resides, and a mission module, which contains the components that store the ammunition and transfer it to the tank. Using FARS, a soldier can remotely transfer ammunition to tanks in a more safe and efficient manner [Ref. 35]. Nevertheless, a soldier is still required to perform the work, and thus continued efforts are directed at removing the human operator from the loop.

The FARS technology has been incorporated into the development of the Future Armored Resupply Vehicle (FARV), which is part of CRUSADER program being conducted by the U.S. Army. The Oak Ridge RPSD is engaged in several projects connected with this program. Its Advanced Integrated Robotics Rearm System (AIRRS) is a "proof-of-principle" activity aimed at demonstrating the technology necessary for automated ammunition processing. Likewise, the Modular Artillery Ammunition Delivery System (MAADS) is focused on the integration of various technologies into a complete artillery ammunition resupply platform. Other projects include the Smart Crane Ammunition Transfer System (SCATS) and Automatic Ammo Identification Technology [Ref. 36].

NASA, through the Jet Propulsion Laboratory, is another Government agency involved in the research and development of technologies for unmanned systems. The JPL has conducted extensive research on wide field-of-view stereo vision for use in vehicle navigation and obstacle avoidance. The passive JPL system can provide detailed range maps from a 256 x 45-pixel area of focus in real-time, at a rate of about 0.6 seconds per frame [Ref. 31]. Continuing development of the stereo vision system is aimed at improving the quality of the range image, integrating terrain classification capabilities, and miniaturizing the computing system [Ref. 33].

JPL work on the Mars Microrover project has addressed two technological obstacles that are also problems for terrestrial UGVs. First, in order to permit a rover to venture beyond the lander's immediate vicinity, it becomes necessary to introduce non-line-of-sight operations. Second, because of the low bandwidths associated with space communications, methods for reducing the amount of communication between the rover and the human operators on earth are also necessary. In dealing with both of these problems, researchers at the JPL have sought to improve the autonomous operation

capability of the rover. For operation beyond line-of-sight to the lander, sensor arrays including proximity, ranging, and machine vision sensors have been added to the vehicle. Several different control architectures have been tried to provide the rover with greater navigational autonomy, allowing for teleoperation at lower bandwidths. The sophistication of these control methods ranges from the CARD (computer-aided remote driving) system, in which a human operator on earth programs the rover's entire path, to a behavior control architecture, in which only an approximate destination is given to the rover and it navigates by reacting to the images provided by its onboard sensors [Ref. 30].

The development of legged robots is another research area that has gained attention recently. The majority of UGV projects have been concerned with wheeled or tracked platforms, such as the high mobility multi-wheeled vehicle (HMMWV) and tank chassis. Walking robots may be particularly suited for use in rugged terrain not easily accessible to other types of vehicles. Walking robots have several advantages over other means of locomotion. In addition to their ability to traverse variable and difficult terrain more readily that tracked and wheeled platforms, they require less power to operate, they can provide a smoother ride, and they are able to integrate mobility with manipulation (i.e., using the legs to lift).

Researchers also associate better balance with walking robots because of the superior stability exhibited by insects and other arthropods which serve as the model for most legged platforms. This advantage has yet to be fully realized; one of the problems suffered by Dante, the most famous legged robot to date (which explored volcanic craters in Antarctica and Alaska), was frequently tipping over. Researching what gives arthropods their excellent balance, scientists found unique sense organs located around their legs that are capable of detecting directional strains on the exoskeleton and regulating their walking accordingly so as to maintain balance. Engineers have since attempted to model these "strain gages" for implementation on robotic platforms. Researchers at Case Western University have built several six-legged robots, employing these strain devices to distribute movement control to the individual legs, thus achieving improved speed and balance [Ref. 13].

The Jet Propulsion Laboratory at NASA is also performing research on legged robots, in cooperation with the Office of Naval Research. The particular aspect of walking robots being studied at the JPL is the gait, one of the most important components of biological locomotion and one also believe to be related to stability. Researchers at the

JPL have produced a simple gait model and developed a control architecture for choosing between different gaits. They have incorporated these on a six-legged robot measuring 0.4 meter long, 0.25 meter wide, and about 0.1 meter in height. Work is still being done on coordinating the movements between the legs for greater stability. For NASA, walking robot technologies are desired for implementation on planetary rovers to make them capable of navigating rocky surfaces [Ref. 31]. The Navy foresees a different application, crablike robots that can operate in shallow water and along shore lines to hunt for mines [Ref. 13].

For many years, DARPA has played a major role in developing technology related to UGVs. In particular, a major 6-year technology base effort just concluded was a collaboration between DARPA and the JRP. DARPA's work on MEMS was discussed in Chapter III. DARPA has also been active in advancing ATR technologies including the introduction of MSTAR (Moving and Stationary Target Acquisition and Recognition), and the development of smart modules, tools designed to offer soldiers enhanced battlefield information and awareness [Refs. 18 and 21].

Another source of robotics research and development is the academic community. Almost every university with an engineering program is involved in some area of robotics. Not all of them, however, are producing results relevant to or advanced enough for application to the JRP. Two university leaders are the University of California at Berkeley and Carnegie Mellon University (CMU), both of which have been active in developing advanced vehicle control technologies related to the Automated Highway System program, as noted in Chapter II. CMU has also been an important participant in the JRP.

Another technology area in which several universities have been particularly active is the development of RSTA capabilities. The University of Massachusetts (UMass) has been one of the prominent participants in this effort, using its Mobile Perception Laboratory (MPL) testbed to help develop advanced sensor technologies [Ref. 41] and evolving stealth navigation capabilities for scout vehicles [Ref. 42].

Another aspect of sensor technology in which UMass has been involved is the development of automatic target recognition (ATR) capabilities, another essential feature for RSTA. Working with Colorado State University and Alliant Techsystems, the project goal has been to enhance existing ATR systems to include algorithms capable of integrating color, forward-looking infrared (FLIR), and LADAR (laser radar) sensor data for superior object recognition [Ref. 17]. The Universities of Maryland, Rochester, and

Pennsylvania have also been working together towards the development of sensor integration for the purpose of target recognition [Refs. 40 and 44].

Under the JRP, the Artificial Intelligence Laboratory at the University of Michigan was tasked with the development of algorithms for multiple vehicle coordination in mission planning, communication, and observation of the environment. Technologies developed at Michigan were incorporated into major demonstrations, and work is continuing there to more fully develop these capabilities [Ref. 43].

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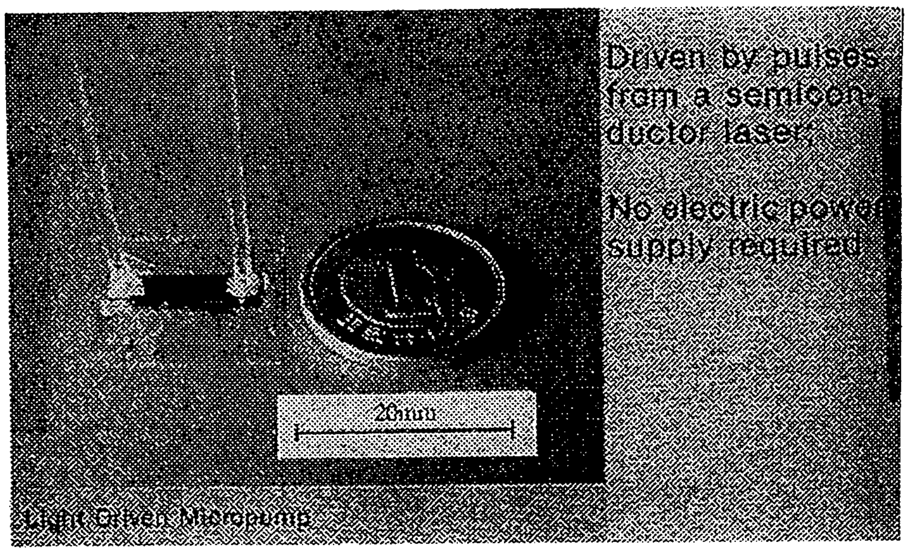
Appendix A

A PHOTO ALBUM OF MICROROBOTIC SYSTEMS

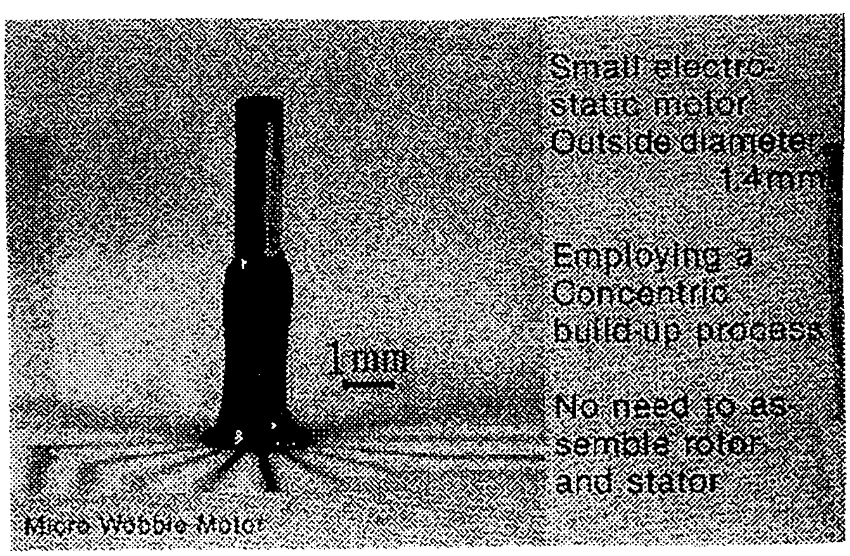
Appendix A

A PHOTO ALBUM OF MICROROBOTIC SYSTEMS

Devices Developed at the
Micromachine Center in Japan [Ref. 28]

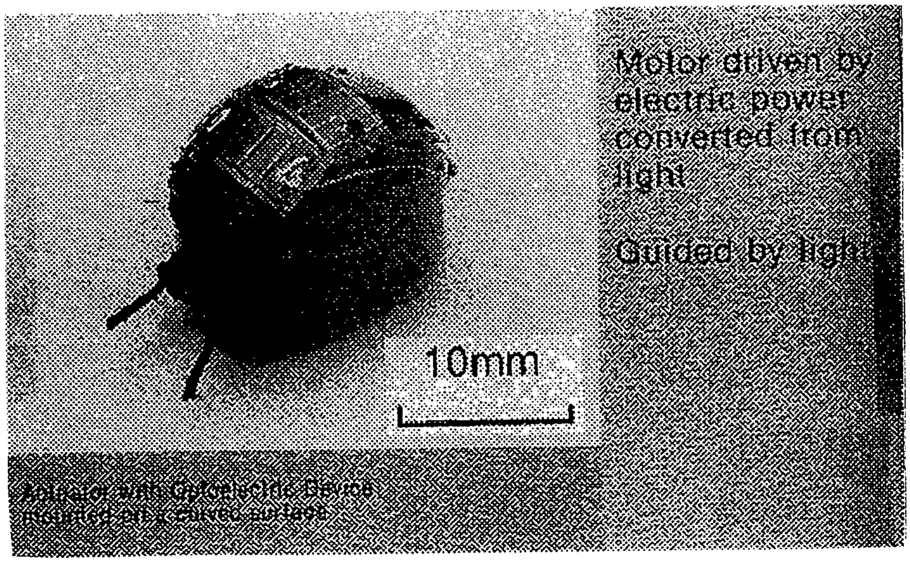


Light Powered Micropump

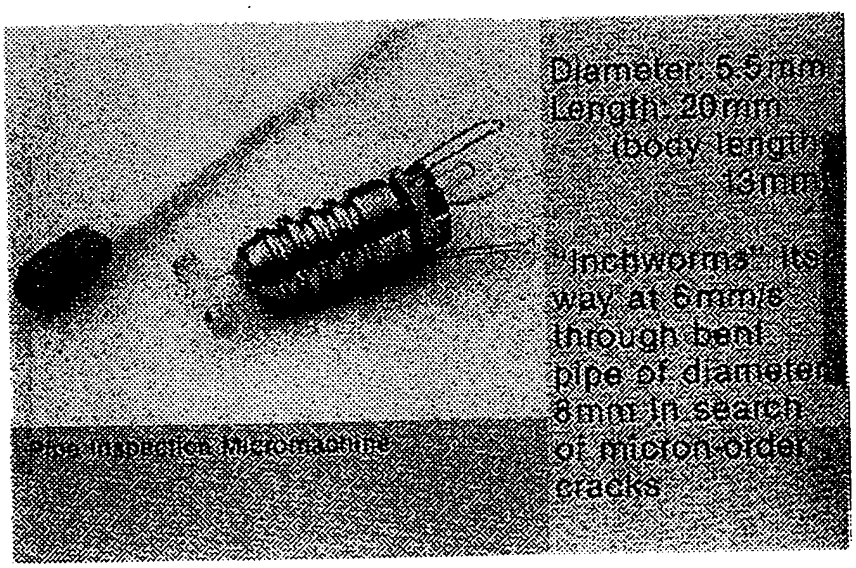


Micro Wobble Motor

Devices Developed at the
Micromachine Center in Japan (cont.)

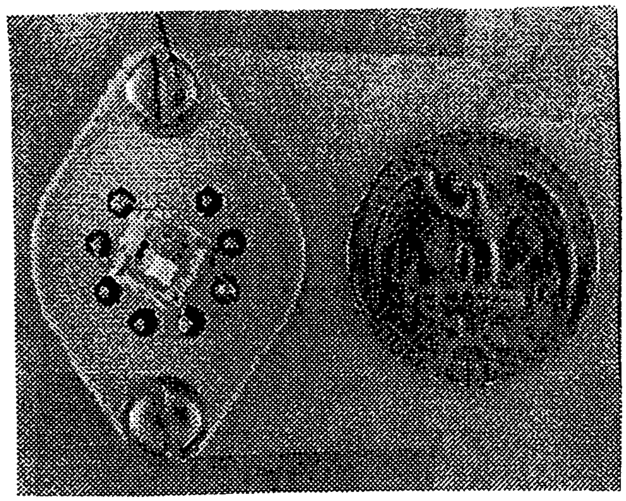


Micro Actuator

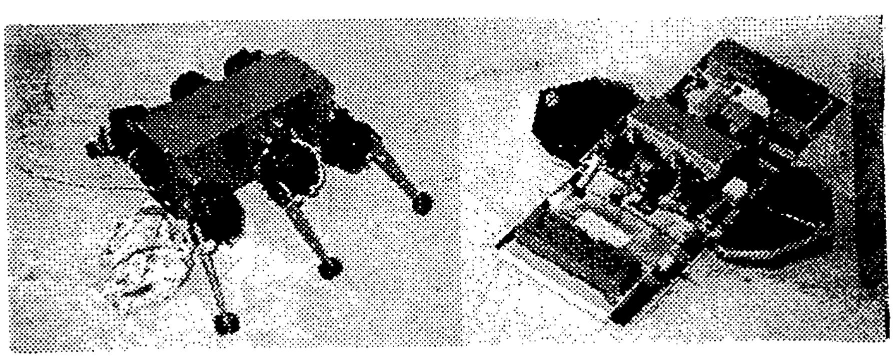


Pipe Inspection Micromachine

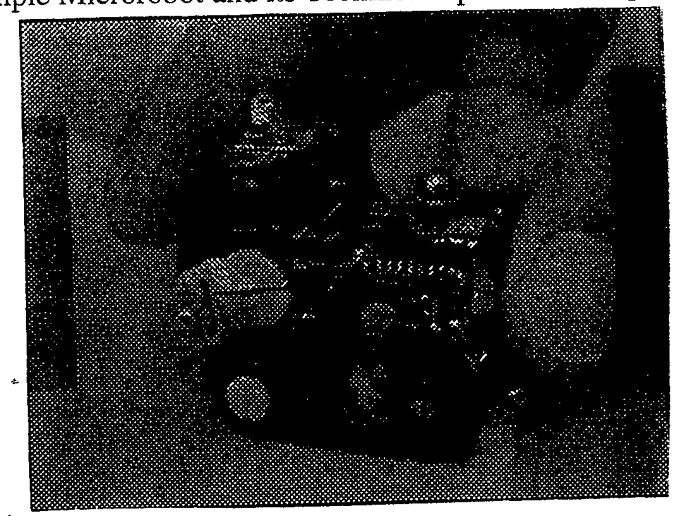
NASA/Jet Propulsion Laboratory
Center For Space Microelectronics Technology
Micro Weather Station [Ref. 29]



IS Robotics
Microrover "Grendel" (left) and
its Deployment System (right) [Ref. 25]



MIT Artificial Intelligence Laboratory
The Ants Project
A Sample Microrobot and its Technical Specifications [Ref. 27]



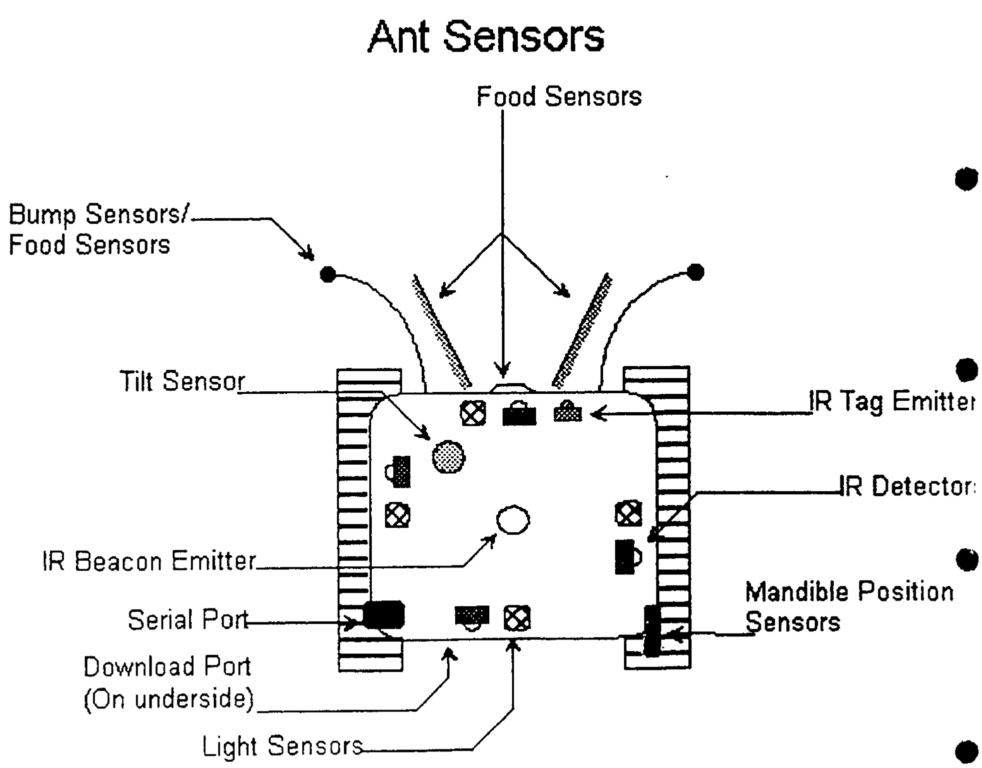
Technical Specifications:
Width (Excluding whiskers): 1.4 inch
Length (Excluding whiskers): 1.4 inch
Height: 1.2 inch
Weight: 1.18 oz.

Total Battery Voltage: 2.4 volts
Battery Type: 1.2 v NiCd cells
Battery Life: 20 min.

Motor Stall Torque: 0.5 oz/inch
Wheel Radius: 0.25 inch
Max Speed: 0.5 ft/sec
Gear Ratio: 59:1

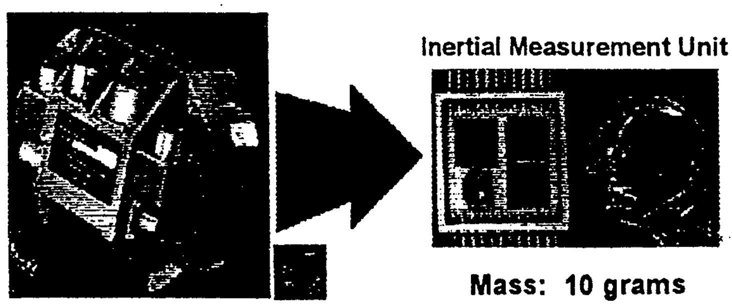
CPU: Motorola M68HC11E9
Clock Speed: 2 Mhz
Memory: 8k EEPROM

4 Infrared Receivers
4 Light Sensors
2 Bump Sensors
5 Food Sensors
1 Tilt Sensor
2 Mandible Position Sensors
1 Battery Voltage Sensor
1 IR Beacon Emitter
1 IR Tag Emitter
3 Mood LEDS



Defense Applications

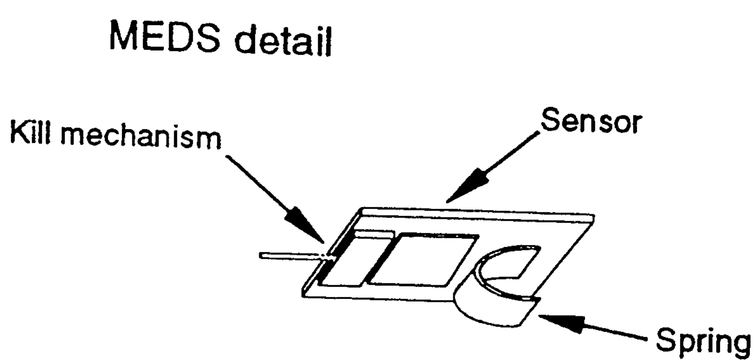
[redacted] [redacted]



Mass: 1587.5 grams
Size: 15 cm x 8 cm x 5 cm
Power: 35 W
Survivability: 35 g's
Cost: $20,000

Mass: 10 grams
Size: 2 cm x 2 cm x 0.5 cm
Power: ~ 1 mW
Survivability: 100K g's
Cost: $500

Inertial Measurement Unit [Ref. 2]
(Microsized compared to Conventional)



Microrobotic Electronic Disabling System Sketch [Ref. 1]

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Appendix B

GLOSSARY

Appendix B
GLOSSARY

ABS	anti-lock braking system
AFAS	Advanced Field Artillery System
AHS	Automated Highway System
AICC	autonomous intelligent cruise control
AIRRS	Advanced Integrated Robotics Rearm System
ALVINN	Autonomous Land Vehicle in a Neural Network
ATR	automatic target recognition
C4	command, control, communications, and computers
CARD	computer-aided remote driving
CMU	Carnegie Mellon University
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DoE	Department of Energy
DoT	Department of Transportation
FARS	Future Armor Rearm System
FARV	Future Armored Resupply Vehicle
FLIR	forward-looking infrared
GPS	global positioning systems
IFF	identification friend or foe
IR	infrared
JPL	Jet Propulsion Laboratory
JRP	Joint Robotics Program

MAADS	Modular Artillery Ammunition Delivery System
MDARS	Mobile Detection Assessment Response System
MDL	Mobile Perception Laboratory
MEDS	Microrobotic Electronic Disabling System
MEMS	microelectromechanical system
MSTAR	Moving and Stationary Target Acquisition and Recognition
NAHSC	National Automated Highway System Configuration
NASA	National Aeronautics and Space Administration
NODS	near-obstacle detection systems
ORTRAN	Oak Ridge Transportation Technology Center
PATH	Partners for Advanced Transit and Highways
RACS	Reduced Access Characterization System
RALPH	Rapidly Adapting Lateral Position Handler
RAMS	Robot-Assisted MicroSurgery
RONS	Remote Ordnance Neutralization System
rpm	revolutions per minute
RPSD	Robotics and Process Systems Division
RSTA	reconnaissance, surveillance, and target acquisition
SARGE	Surveillance and Reconnaissance Ground Equipment
SCATS	Smart Crane Ammunition Transfer System
SMART	Sequential Modular Architecture for Robotics and Teleoperation
UGV	unmanned ground vehicle
UXO	unexploded ordnance

Appendix C

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Commandant U.S. Army Infantry School Attn: ATSH-WCB-C Fort Benning, GA 31905-5400	1
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This paper describes the results of a literature search aimed at describing activities that are developing technologies of potential importance to future military unmanned ground vehicles (UGVs). It focuses on three such areas: the Automated Highway System program, microrobotics and microelectromechanical systems (MEMS). The potential for technology transfer from these activities to military UGV projects is discussed.

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